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# TUBE-LAUNCHED ROCKET PERFORMANCE

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## SUMMARY

Imparting an initial velocity to rocket vehicles using an ejection tube can result in significant performance gains. Curves are presented that show orbital payload and ballistic range increases as a function of tube muzzle velocity (0 to 1000 ft./sec.) and tube length (0 to 1400 ft.). Results are shown for both fixed-design vehicles (Atlas/Centaur, Saturn IB/Centaur, and a two-stage solid rocket similar to Minuteman) and a "rubber-design" hypothetical three-stage solid propellant vehicle. The "rubber-design" vehicle is optimally staged to take maximum advantage of tube launching. The gains are proportional to the so-called gravity losses of the conventional launch case. Thus, the gains are higher for low-performance vehicles rather than high-performance vehicles. For instance, low initial thrust-to-weight ratio ($F/W_1$) vehicles benefit more than high $F/W_1$ vehicles and constant-thrust vehicles more than constant-acceleration vehicles. For existing chemical rockets, payload gains of 13 percent are possible with 500-ft. long tubes. For future rockets with 15 g peak ejection load capabilities, the gain could be as high as 21 percent greater than conventional launches. For high $F/W_1$ rockets, the launch tube must be inclined away from the vertical to realize the full performance potential. The peak dynamic pressure and heating rate are less for tube launches than conventional launches for most muzzle velocities.

## INTRODUCTION

Various ideas have been suggested for imparting initial velocities to rockets. Such a scheme would increase the payload or range of a rocket for a given amount of propellant. For very small rockets, the gun launch system used in Project Harp (ref. 1) is capable of quite high muzzle velocities. A 5500 ft./sec. muzzle velocity is possible for a 2000-lb. three-stage rocket that inserts a 50-lb. payload in orbit. Kumar, et al. (ref. 2) studied the case of a vacuum-air boost system where the driving force is obtained by evacuating a vertical launch tube with a breakable seal at the top and a pressure seal about the missile at the bottom. When the missile is released, air pressure accelerates the missile upward through the tube. Kumar, et al., concluded that 800 ft./sec. is feasible for gross weights up to about 80,000 lbs., but a compressed-gas system would be required for larger missiles. Several military applications of compressed-gas systems are already in use (ref. 3). Cohen and Micheli (ref. 4) studied the internal ballistics of a boost system that used a gas generator at the bottom of a launch tube. Another tube boost system is the active rocket scheme wherein the rocket itself provides the pressurization gas (ref. 5).

The motion of the missile within the tube was analyzed in these studies but not the rocket performance gains (except for Project Harp). Foa (ref. 6) evaluated the performance gain of ejected sounding rockets for the restricted case of vertical flight, no drag, infinite stages, and fixed burnout velocity. The present study takes a brief look at the potential performance advantages of launch tubes for orbital and ballistic range missions. Certain tradeoffs of a secondary nature were not performed. For example, tube length could be shortened if the rocket vehicle were strengthened to withstand high g-loads during the tube ejection phase. This is probably impractical for existing vehicles. Furthermore, other constraints such as payload acceleration limits might preclude such a tradeoff. For the orbital mission, results are presented for two existing vehicles (Atlas/Centaur and Saturn IB/Centaur) and a hypothetical three-stage solid propellant vehicle. For the ballistic range problem, a two-stage solid rocket similar to Minuteman was assumed. Table I presents a data summary for all the rockets.

There are, of course, many other factors that also affect the attractiveness of tube launchers. Design and construction problems would be appreciable and there would be problems in modifying any existing vehicle for use of this scheme. On the other hand, tube launchers make vehicles less sensitive to low altitude turbulence or gusts. The present analysis relates performance to launch parameters for various launch vehicles. The important consequences of tube launching on such factors as vehicle design, construction, aerodynamics, payload constraints, and economics are not considered.

## ANALYSIS

The performance determination may be split into two parts: (1) that part concerned with the ejection process, and (2) that part concerned with the post-ejection ascent. The post-ejection ascent is the main concern here because it alone determines the payload and ballistic range gains once the muzzle velocity is specified. Thus, the performance gains apply for all ejection schemes. These gains were computed by fixing the initial mass at ejection and using computer programs to determine ascent trajectories.

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A zero angle-of-attack thrust program was assumed for the first stage and variational thrust programs for the final two stages. For Atlas/Centaur, the variational thrust program was initiated at booster engine cutoff (BECO). The optimum launch angle (tube deflection from vertical) was also determined. For the hypothetical three-stage solid rocket, the stage propellant loadings were optimized and an optimum duration interstage coast period was placed ahead of third stage ignition. The liquid rockets were stage-fixed and without coast periods.

## Ballistic Range

The only ballistic range vehicle assumed was a hypothetical two-stage solid rocket that resembles Minuteman. It was assumed to have fixed stages, constant thrust, $F/W_1$ equal to 3, and a range of 6100 st. miles for conventional launches. Both vertical launch and optimized launch angle cases were computed. For vertical launches, the angle-of-attack program for each stage was taken to be a quadratic function of time with coefficients optimized to maximize range. For optimum angle launches, the first stage angle-of-attack program was set to zero for simplicity and because it is nearly optimal for this case.

## Tube Length Calculations

Relating performance gains to launch tube characteristics such as tube length necessitates defining an ejection system and making a detailed analysis to describe the vehicle motion during the ejection process. To get a rough idea of how tube length is related to muzzle velocity, a simple tube pressure history was assumed; namely,

$$p = p_{max} \sin (\pi \, ^t/t^*) \qquad (1)$$

where p is the tube pressure (net pressure difference across the rocket), $p_{max}$ is the peak tube pressure, t is time, and t* is the tube escape time. The rocket motion equation during the ejection phase is:

$$\frac{d^2X}{dt^2} = \frac{A}{m} \; p - g \cos \theta \qquad (2)$$

where X is distance along the tube, m is rocket mass, A is tube cross-sectional area, g is gravity, and θ is the tube launch angle. Together, these equations yield the following relationship between tube length L and muzzle velocity V:

$$L = \frac{V^2}{\frac{4}{\pi}(\ddot{X}_{max} + g \cos \theta) - 2 g \cos \theta} \qquad (3)$$

where $\ddot{X}_{max}$ is the peak acceleration during the ejection process.

In the active rocket scheme, some of the rocket's propellant is consumed during the ejection process. The amount of propellant consumed is generally quite small and is ignored in this study.

## RESULTS

Several curves of performance gains versus muzzle velocity are presented in figure 1. The lower part of the figure shows payload gains. The Atlas/Centaur and the Saturn IB/Centaur results were so close together that only a single curve was plotted for both. The hypothetical constant-thrust solid rocket benefits most from an ejection launch while the constant-acceleration rocket benefits least. This is to be expected since the gravity losses are greatest for the constant-thrust solid (total loss is 4800 ft./sec.) and least for the constant-acceleration solid (total loss is 2000 ft./sec.). The time average acceleration is much higher for the constant-acceleration rocket (F/W is always 6) then the constant-thrust rocket (F/W varies between 1.5 and 6). The constant 6 g acceleration vehicle is quite efficient to begin with and, therefore, does not benefit so much by an ejection scheme. Since gravity losses are reduced as the average F/W is increased, performance gains are greatest for low F/W vehicles.

The payload gains are large for the higher muzzle velocities, reaching 38 percent at1000 ft./sec. for the low performance solid rocket with $F/W_1 = 1.5$. The fact that the solid rockets were optimally designed (i.e., stage propellant loadings and coast phase) rather than fixed as for the two chemical vehicles is not too important. The performance gains were affected very little by changing the stage propellant loads and coast duration. Consequently, muzzle velocity and average F/W are the only variables that strongly affect the performance gains.

The upper part of figure 1 gives the ballistic range gains for the ICBM type solid rocket. Curves for both vertical launch and inclined launch are shown. The range increases are generally about the same as the payload-to-orbit gains. The decrease in gain that results from restricting launches to vertical inclinations is readily apparent. The amount of decrease shown should not be taken as indicative for all rockets. This is illustrated on figure 2 where the optimum tube launch angle is plotted as a function of muzzle velocity and $F/W_1$. Higher $F/W_1$ vehicles require more tipping away from the vertical to derive maximum performance gain. Thus, high $F/W_1$ rockets suffer in performance more than low $F/W_1$ rockets if they are constrained to vertical launches. This aspect favors low $F/W_1$ rockets since vertical launch tubes are more feasible than an inclined tube, especially when various launch azimuths are considered. Thus, low $F/W_1$ rockets are more attractive candidates for tube launching because of their higher gain potential and their compatibility with simple vertical tubes.

The attractiveness of tube launches is lessened by tube length considerations. With the important assumption ($p = p_{max} \sin \pi\, ^t/t^*$) concerning the tube ejection process, the performance gains may be plotted as a function of tube length using figures 1-2 and equation (3). This is done in three parts in figure 3. Part a shows the payload-to-orbit case assuming that the maximum acceleration during the ejection process, $\ddot{X}_{max}$, is 6 g. Part b is for the ballistic range case assuming $\ddot{X}_{max}$ is 8 g. Payload and range gains are between 7 and 14 percent for 500 ft. long tubes. The associated muzzle velocities are 325-400 ft./sec. The $\ddot{X}_{max}$ chosen above represents real structural limits for the existing chemical rockets and assumed limits for the hypothetical solid rockets. The effect of increasing

$\ddot{X}_{max}$ is shown in part c of this figure. For the constant-thrust solid rocket ($F/W_1 = 1.5$) and 500 ft. tubes, the payload gain jumps from 13.7 percent to 21.5 percent as $\ddot{X}_{max}$ is increased from 6 g to 15 g. The payload benefits shown here represent upper limits since structural weight increases were not accounted for as $\ddot{X}_{max}$ increased. It is clear, however, that tube launching is most attractive for low $F/W_1$ rockets that are able to withstand high ejection acceleration. Otherwise, excessive tube lengths are required to realize significant performance gains.

The constant-thrust, low $F/W_1$ solid rocket is the most attractive candidate for a tube launching scheme and the remainder of the study concentrates on it further. The effect of $F/W_1$ on payload ratio is shown on figure 4 for three muzzle velocities V. Changes in engine and structure weight with $F/W_1$ were ignored in this simple analysis. In terms of payload gain, imparting 500 ft./sec. to a rocket is equivalent to raising $F/W_1$ from 1.5 to 2.0. Imparting 1000 ft./sec. is equivalent to raising $F/W_1$ to 3.3. The amount of payload increase due to an increase in V is nearly independent of $F/W_1$. This accounts for the higher percentage increase in payload at lower $F/W_1$. This is also true for the constant acceleration rocket shown here for comparison.

Also shown on figure 4 is the maximum dynamic pressure $q_{max}$ as a function of $F/W_1$ for $V = 0$. This curve shows that increasing $F/W_1$ causes $q_{max}$ to increase rapidly to values considerably beyond those attained in current practice (about 950 lb./ft.$^2$). At $F/W_1 = 1.5$, $q_{max}$ is about 930 lb./ft.$^2$ But for $F/W_1 = 2.0$, $q_{max} = 1800$ lb./ft.$^2$ and for $F/W_1 = 3.3$, $q_{max} = 5800$ lb./ft.$^2$. A later curve will show that for $F/W_1 = 1.5$ and V less than 880 ft./sec., $q_{max}$ is less than 930 lb./ft.$^2$ Tube launching therefore alleviates the $q_{max}$ problem rather than aggrevates it as does increasing $F/W_1$.

The trajectories of tube launched rockets differ little from those of conventionally launched rockets. This is illustrated in figures 5 and 6 for the orbital mission. The tube launched rocket prefers slightly more coast time and therefore attains orbital conditions further downrange. It also attains transonic speeds at lower altitudes--but Mach numbers greater than 1.5 occur at higher altitudes. The time histories of dynamic pressure q, axial load factor, and heating rate factor are displayed on figure 7. Initially, the q history improves as V increases and then it becomes worse. This behavior is due to the combined effect of density and velocity histories. For small V, density decreases faster than the velocity squared increases; and this leads to a decrease in $q_{max}$. For V less than 880 ft./sec., $q_{max}$ is less than the conventional launch $q_{max}$. Thus, tube launches cause $q_{max}$ to decrease for the lower (and useful) values of muzzle velocity. The same is also true for the heating rate and the first stage burnout q.

## CONCLUSIONS

1. The prime candidates for tube ejection launch schemes are low acceleration, constant-thrust rockets. Such rockets have the highest potential performance gain and do not require off-vertical tube angles to realize their potential.

2. The gains are modest for practical tube lengths. Up to 14 percent payload gains are possible with 500 ft. long tubes and conventional rocket structures. Strengthening the structure to withstand a 15 g peak ejection load could raise the gain to as much as 21 percent if the structural weight penalties are neglected. Inclusion of the weight penalties into the analysis would reduce and could even eliminate the gains due to increasing the peak ejection load. Nevertheless, the potential gain for future rockets is greater than that for present rockets since the required structure could be incorporated into the original design rather than require possibly extensive modification of an existing design.

3. Initial thrust-to-weight ratio ($F/W_1$) is the primary gain-determining factor. Propellant type (solid or liquid) and stage propellant loadings have only a minor influence on performance gains.

4. High $F/W_1$ rockets require inclined tubes to take full advantage of tube launching schemes. Since the azimuth angle varies for different missions, tube launches for high $F/W_1$ rockets are probably only attractive for small rockets. This is because large, variable azimuth angle tubes would be difficult to build.

5. The maximum dynamic pressure, first stage burnout q, and heating rate are less for tube launches than conventional launches for practical muzzle velocities.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio June 27, 1967

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TABLE I - ROCKET DATA

| Rocket | Mission | $F/W_1$ | $F/W_2$ | $F/W_3$ | $I_1$ | $I_2$ | $I_3$ | $MF_1$ | $MF_2$ | $MF_3$ | $\frac{W_1}{A_1 C_{D_{max}}}$ | $\frac{W_{PL}}{W_1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Atlas/Centaur | Orbital | 1.17 | 0.665 | - | 292 | 442 | - | 0.928 | 0.88 | - | 5400 | 0.0351 |
| Saturn IB/Centaur | Orbital | 1.43 | 0.69 | 0.55 | 296 | 428 | 443 | 0.89 | 0.88 | 0.76 | 8500 | 0.0285 |
| 3-Stage Solid | | | | | | | | | | | | |
| a)constant thrust | Orbital | 1.5 | 1.4 | 2.2 | 260 | 275 | 275 | 0.905 | 0.916 | 0.877 | 8500 | 0.0166 |
| b)constant accel. | Orbital | 6 | 6 | 6 | 260 | 275 | 275 | 0.905 | 0.916 | 0.877 | 8500 | 0.0255 |
| 2-Stage Solid Constant Thrust | Ballistic Range | 3 | 3 | - | 253 | 300 | - | 0.818 | 0.896 | - | 5300 | 0.0118 |

FW = initial thrust/weight ratio; I = vacuum specific impulse; MF = mass fraction, (propellant)/(propellant + structure); $W_1/A_1\, C_{D_{max}}$ = ballistic coefficient (lb./ft.$^2$); $W_{PL}/W_1$ = payload ratio for conventional launch.

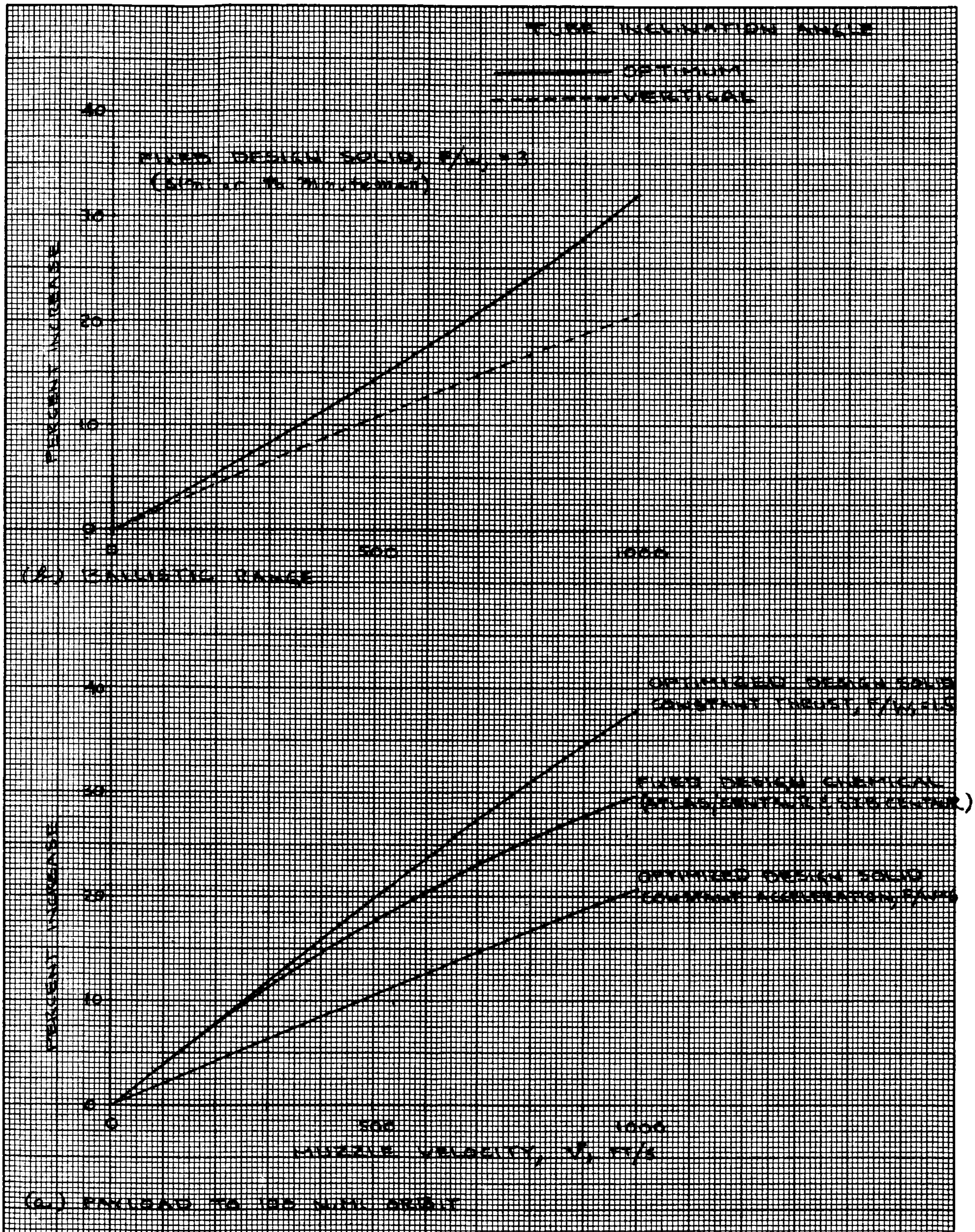


FIG 1 PERFORMANCE GAINS FOR LAUNCH TUBE EJECTION

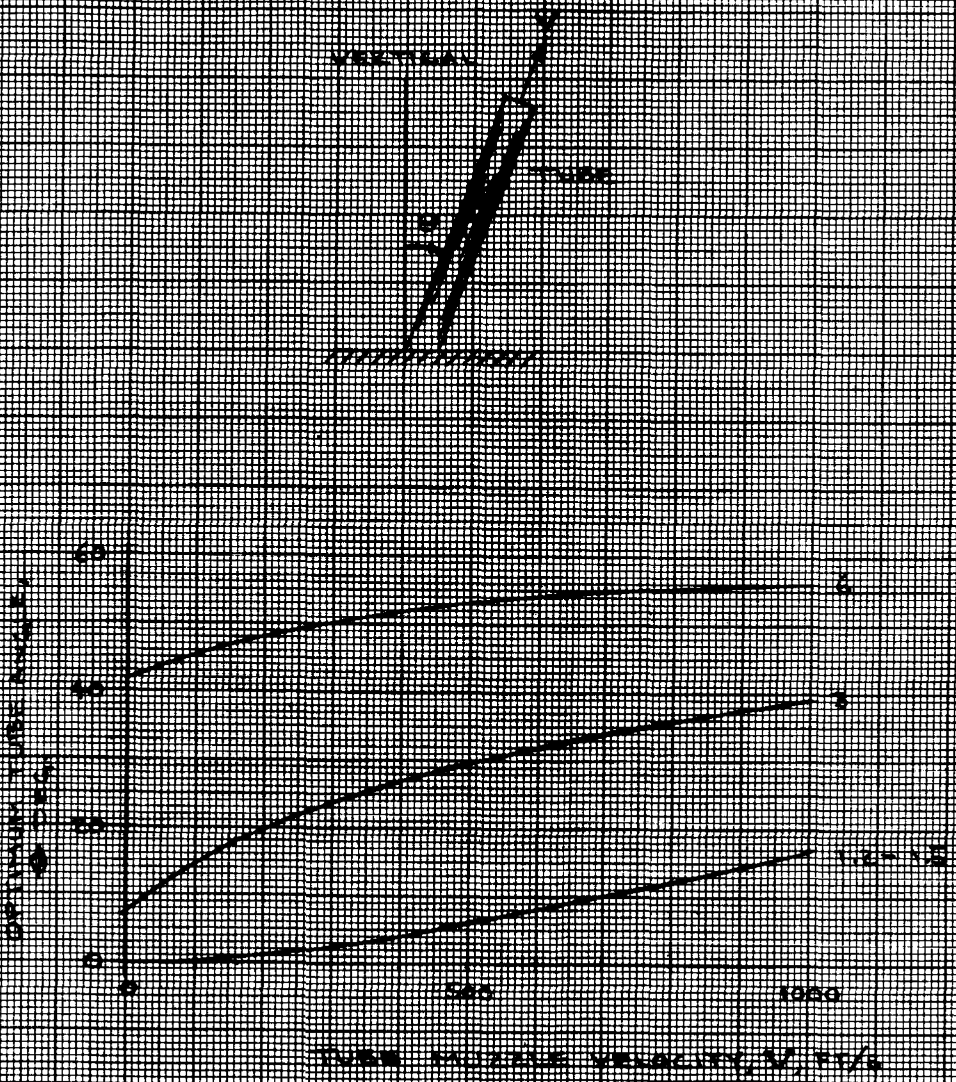


FIG. 2 OPTIMUM LAUNCH ANGLES ORBITAL & BALLISTIC RANGE MISSIONS

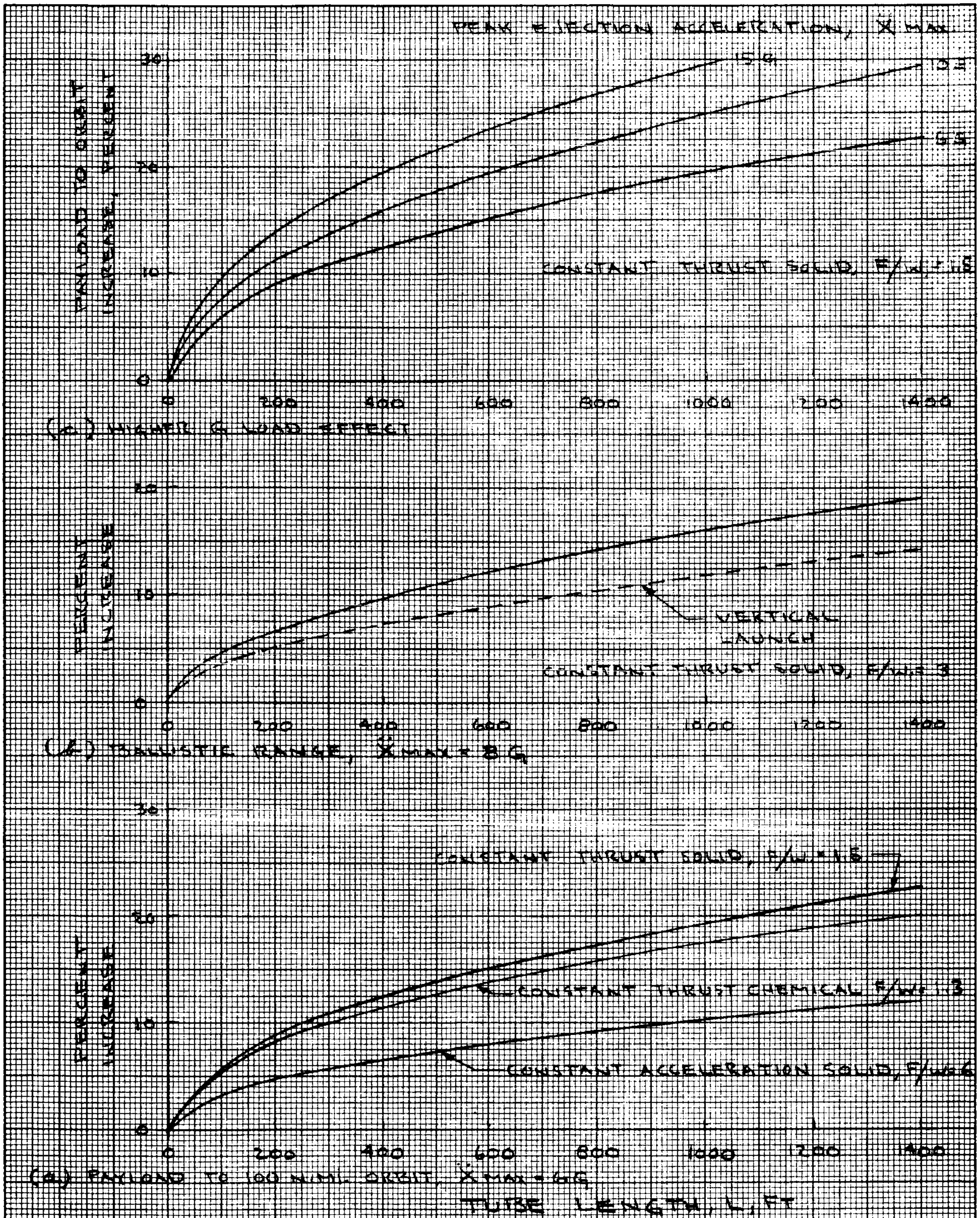


FIG. 3 PERFORMANCE GAIN V.S. TUBE LENGTH FOR SINE WAVE PRESSURE HISTORY. OPTIMUM TUBE LAUNCH ANGLE.

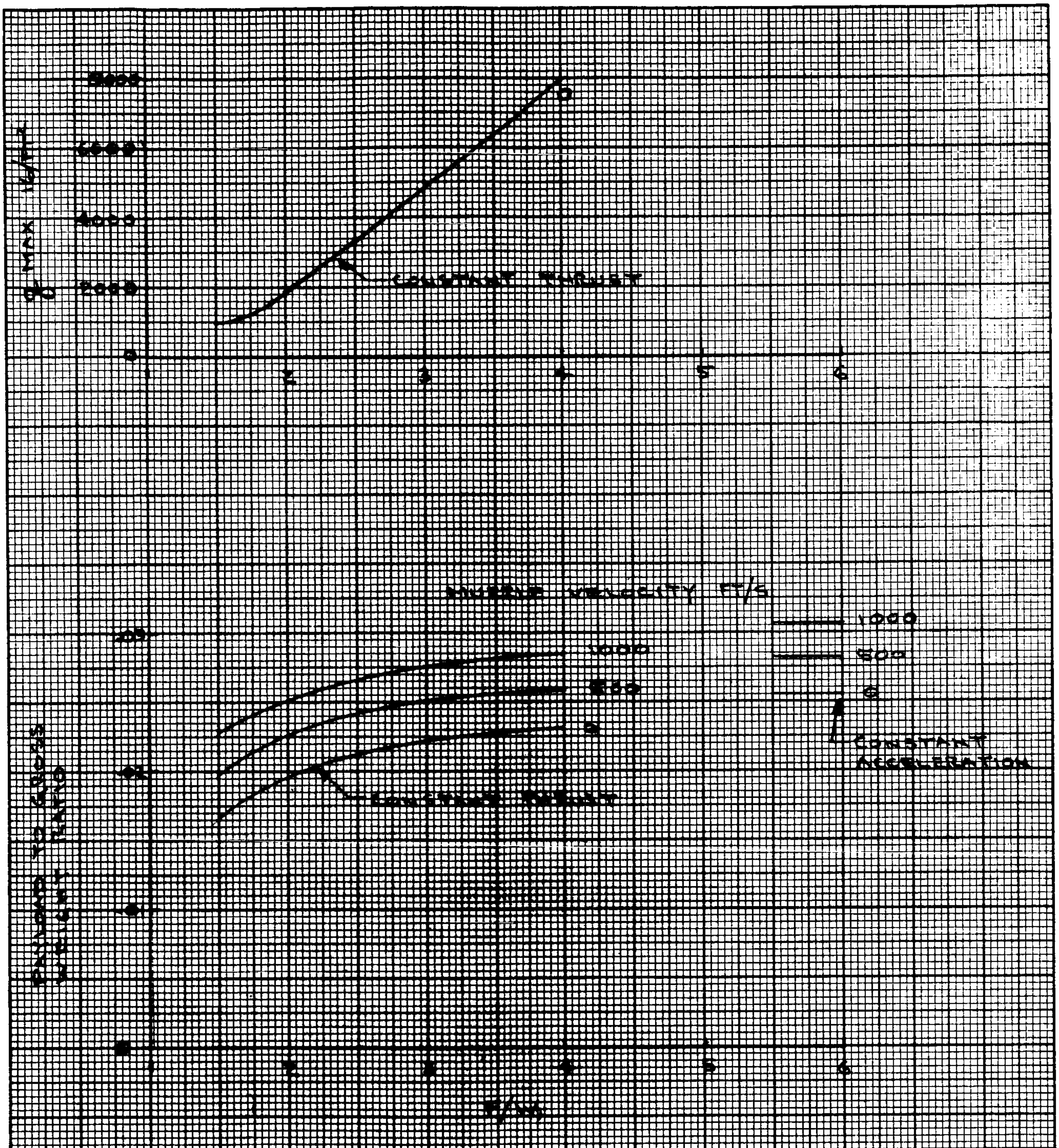


FIG. 4 EFFECT OF F/W ON PAYLOAD RATIO ([illegible] N.MI. ORBIT) & PEAK DYNAMIC PRESSURE FOR 3 STAGE SOLID ROCKET.

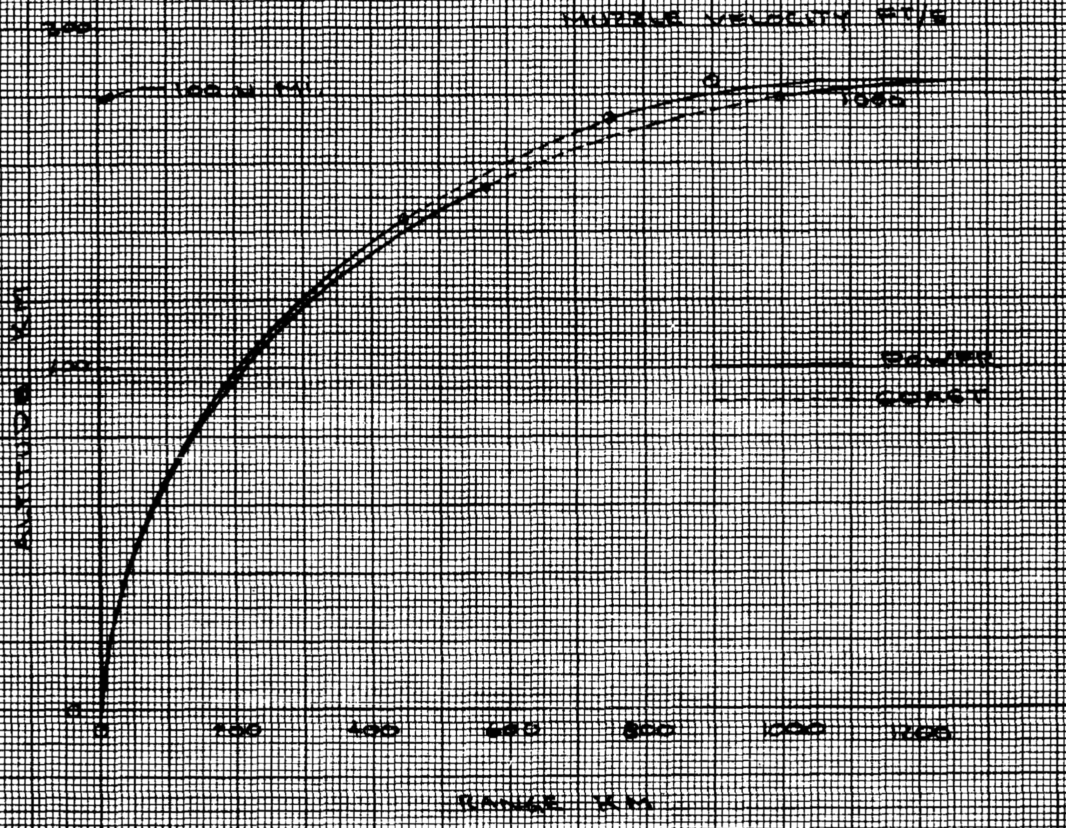


FIG. 5 TRAJECTORY PLOT FOR CONVENTIONAL AND TUBE LAUNCHED 3-STAGE SOLID ROCKET. $F/W = 1.5$, $F/W_2 = 1.4$, $F/W_3 = 2.2$

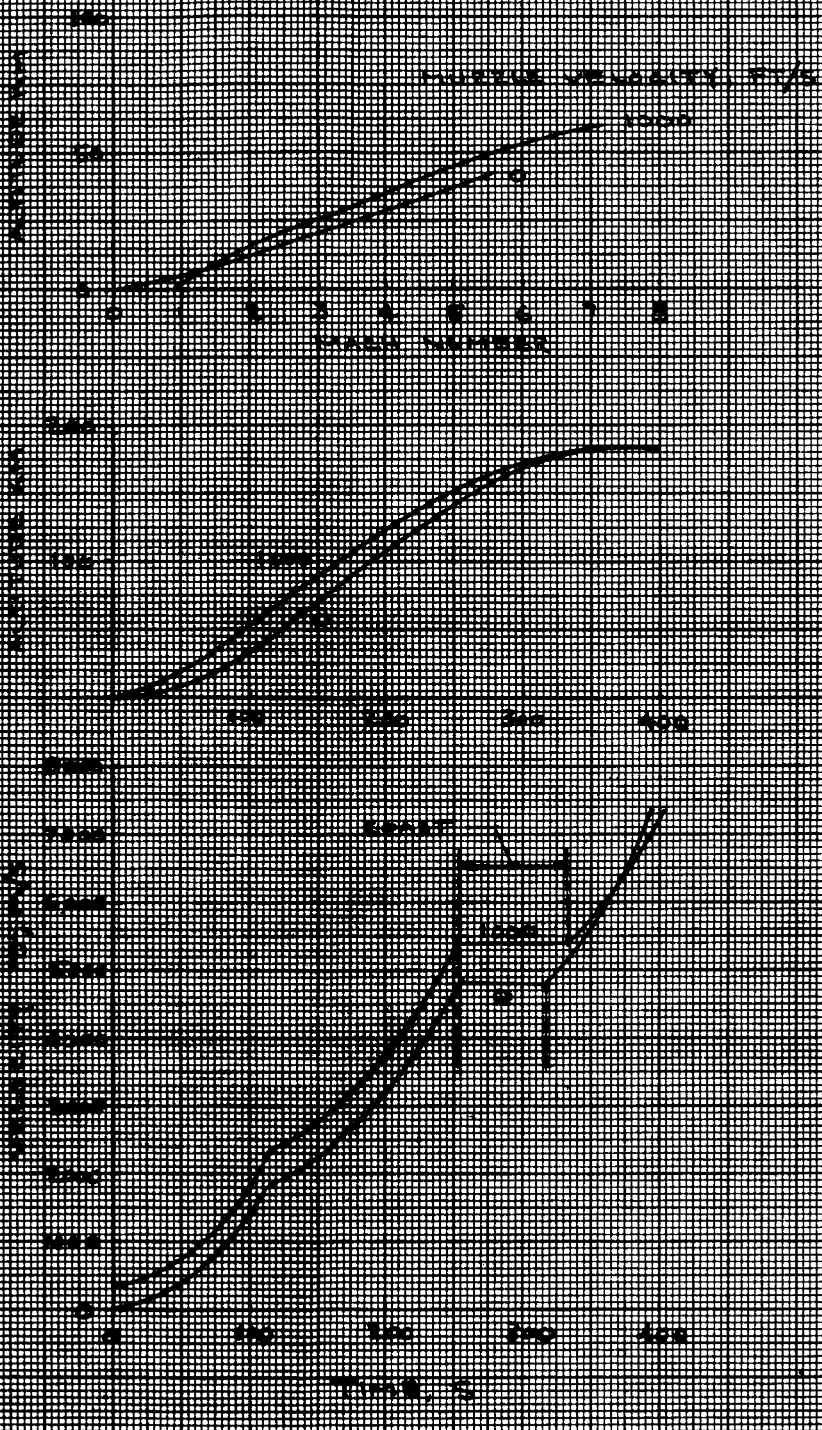


FIG. 6 COMPARISON OF TRAJECTORY VARIABLES FOR CONVENTIONAL & TUBE LAUNCHED ROCKETS
3-STAGE SOLID ROCKET F/w1=1.5, F/w2=1.4, F/w3=2.2

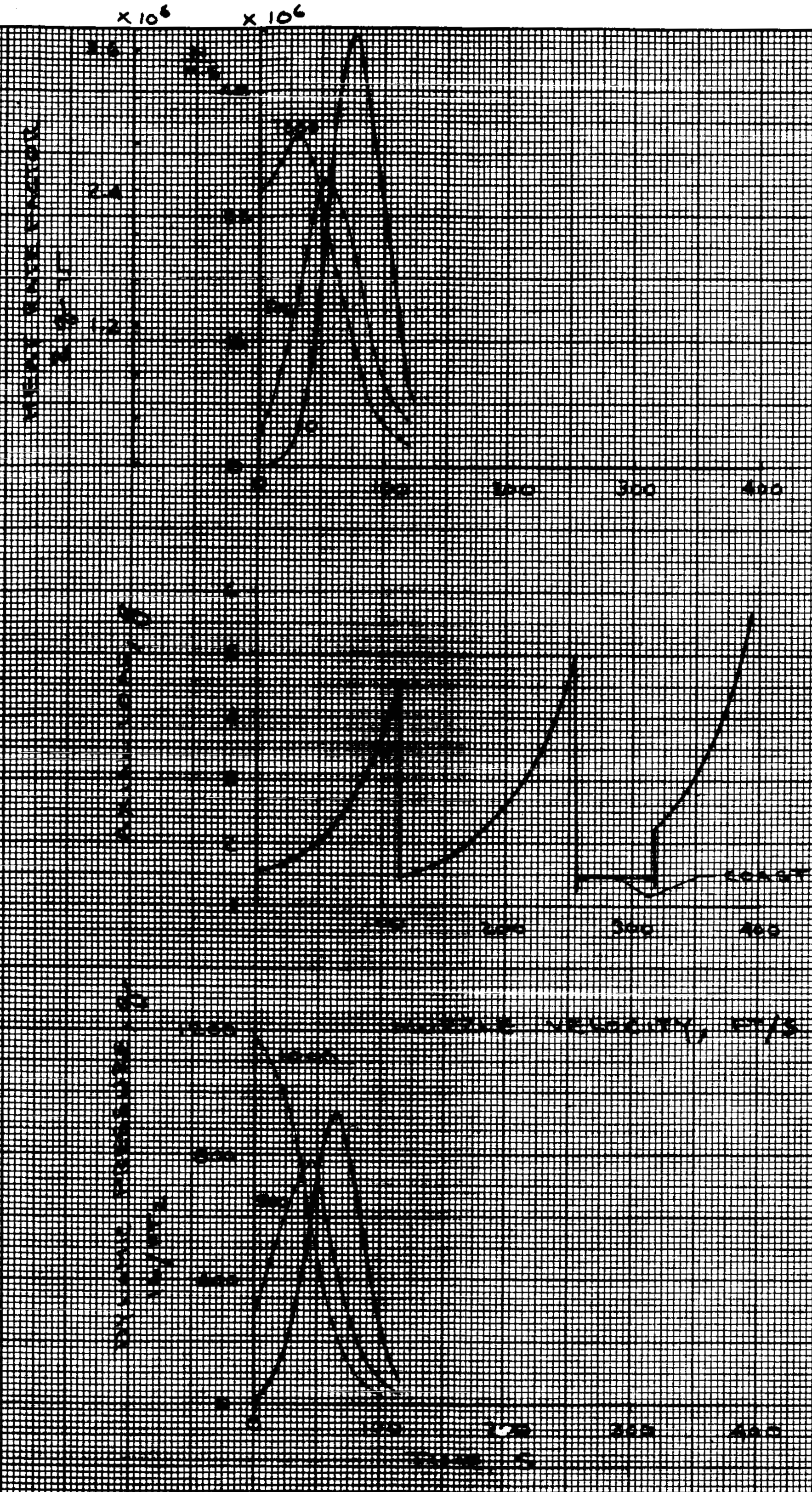


FIG. 7 DYNAMIC PRESSURE, AXIAL LOAD & HEAT RATE FACTOR HISTORIES FOR CONVENTIONAL & TUBE LAUNCHED 3-STAGE SOLID ROCKET

$F/W_1 = 1.5$, $F/W_2 = 1.4$, $F/W_3 = 2.2$